# The CERES S'COOL Project:
# Statistical Analysis of Cloud Data Collected by Satellites with Comparisons to Simultaneously Collected Ground Data

Amanda Falcone*

Department of Physics
Hampton University
Hampton, VA 23668

**Abstract**

The CERES (Clouds and the Earth's Radiant Energy System) project will provide data over an expected span of 15 years that will lead to better understanding of the role of clouds in the Earth's energy cycle and in global climate change. Understanding clouds, where they occur, and their characteristics are thought to be the keys to understanding climate changes. An integral part of the CERES project is known as the S'COOL (Students' Cloud Observations On-Line) Project. The purpose of S'COOL is to have ground observations for comparison with the satellite data. Over 500 schools around the globe provide information from the ground about the clouds as the CERES instrument orbits overhead on a satellite. This "ground truth" provides one way to ensure that the instruments are functioning properly and clearly identifying all of the clouds, and identifying the clouds correctly. These two sets of data, from the CERES instruments and from the schools around the globe, will be compared and analyzed using statistical methods in order to compare the level of agreement between the datasets. The agreement of these results will help to validate the CERES data, and aid in a better understanding of the shortcomings of current forms of measurement.

*"…the science of Nature has been already too long made only a work of the brain and the fancy; It is now high time that it should return to the plainness and soundness of observations…"* *- Robert Hooke (1635-1703)*

# 1 Introduction

The Clouds and the Earth's Radiant Energy System (CERES) project is one of the highest priority undertakings of NASA Langley Research Center's Atmospheric Sciences research (ref: CERES Homepage). The project is a part of the Earth Observing System (EOS), which is an international program for studying the Earth from space using a multiple instrument, multiple satellite approach (ref: EOS Homepage). CERES is an experiment that will build upon the discoveries of previous missions such as the Earth Radiation Budget Experiment (ERBE) (ref: ERBE Homepage). The purpose of the experiment is to lead to a better understanding of the role of clouds in the Earth's energy cycle and their relationship with possible global climate change.

Clouds play a major role in determining the climate of the Earth. The sun provides the radiant electromagnetic energy that fuels the Earth's climate (CERES Brochure, 1999). One of the many functions of the atmosphere is to maintain a balance between energy received from the sun and energy radiated from the Earth. Energy received from the sun is mostly in the form of visible (shortwave) radiation, while the energy radiated back into space by the Earth is mostly of the infrared (longwave) type of radiation. The balance between incoming and outgoing electromagnetic radiation is called the Earth's radiation budget.

Important components to the radiation budget are the planet's surface, atmosphere, and clouds. Knowledge of the occurrence and characteristics of clouds is essential to understanding global climate change. The difference between clear-sky and total-scene radiation results is known as cloud-radiative forcing, and this is a measure of the effect that clouds have on the Earth's radiation balance. Different types of clouds affect the radiation budget differently, mainly because of their composition and temperature. High, thin, cirrus clouds warm the Earth's surface because they allow most of the shortwave radiation through, while trapping some of the longwave radiation. Low stratus clouds have an overall cooling effect because much of the solar energy is reflected while the longwave energy from the Earth is readily emitted into space. Finally, convective clouds are somewhat neutral because the solar energy is reflected but at the same time the longwave radiation is retained.

Optical depth, a general measure of the capacity of a cloud or a region of the atmosphere to prevent the passage of light, is a major contributing factor to the manner in which clouds affect the climate. In general, greater optical depth creates a greater blockage of radiation from the sun, which results in a greater cooling in the Earth's atmosphere and surface. Optically thick clouds reflect more shortwave radiation than would the dark surface of the Earth. This results in less solar energy reaching the surface of the Earth and the atmosphere for heating, which in turn results in an overall cooling effect.

The intensity of thermal emission of a cloud varies not only with optical depth, but also with temperature. Tops of clouds are typically colder than the Earth's surface. If a cloud forms where there had been previously clear sky, the cloud creates a type of barrier in the atmosphere to the energy being emitted from the Earth. The Earth radiates energy at a set temperature and instead of passing all this energy right into space, the cloud absorbs some of the radiation. The cloud then radiates energy in all directions; however, this energy is at the temperature of the cloud, which is much cooler than the temperature of the Earth. This results in a small amount of energy leaving the atmosphere, rather than the large amount radiated by the Earth, which results in a net heating of the Earth and the atmosphere.

The CERES project will help in determining how human activities are affecting what types of clouds are formed, and how these clouds are affecting the overall climate of the Earth. Explanation of the data collection of CERES is in section 2.

The S'COOL project provides "ground truth" data that will aid in verification of the CERES satellite data (ref: S'COOL Homepage). The ground truth is provided by an increasing number of participating schools (currently 544) and then compared with data from the satellite. These two sets of data, in conjunction with other Earth Science Enterprise activities, will help in developing an overall view of the climate.

# 2 Collection of Data

## 2.1 CERES algorithm

The CERES instrument is superior to previous similar instruments in many different ways of measurement. For scene identification, the CERES instrument identifies clouds using collocated high-spectral and spatial resolution cloud imager radiance data (Wielicki et. al 1998). These data are from the same spacecraft as the CERES broadband radiance data, which measures the entire shortwave and longwave spectra to assess the Earth's radiation budget. Only specific channels are used in identifying the clouds, and specific imagers on the spacecraft gather these data. On the Tropical Rainfall Measuring Mission (TRMM), which was launched in November 1997, CERES uses the Visible Infrared Scanner (VIRS) which has 2 kilometer spatial resolution, a 1.6 μm channel for improved cloud microphysics, and a deployable solar diffuser plate to monitor long term instrument gain stability (ref: TRMM Homepage).

On Terra, which was launched in December 1999, and on Aqua, scheduled to be launched in December 2000, CERES uses the Moderate Resolution Imaging Spectroradiometer (MODIS) (ref: Terra Homepage). MODIS has spatial resolutions varying from 250 meters to 1 kilometer, with several additional cloud remote sensing spectral channels and greatly improved solar spectral channel calibration, including the ability to use the lunar surface as a stability calibration target. Using these new techniques, CERES identifies clouds by cloud amount, height, optical depth, and cloud particle size and phase. It will hopefully also be able to classify clouds as single or multilayered.

The imagers used to derive cloud properties for CERES measure at several spectral channels to determine optical depth, cloud particle size, and phase of cloud. The VIRS instrument on TRMM measures at 0.65 μm, 1.6 μm, 3.7 μm, 10.8 μm and 11.9 μm. The MODIS instrument on Terra and Aqua measures at the same wavelengths, plus 2.1 μm, and 8.5 μm, along with other channels used for different purposes. These channels allow the instruments to collect a great deal of spectral information useful for cloud remote sensing.

CERES also uses a rotating azimuth plane (RAP) scanner that enables it to sample radiation across the entire hemisphere of emitted and scattered radiation. These data will be paired with cloud imager derived cloud properties to develop a more complete set of models of the clouds including physical and radiative properties in both the shortwave and longwave regions of energy. In order to improve time sampling, CERES will use data from three hourly geostationary satellites. This will aid in determining the fluxes at the top of the atmosphere (TOA) by interpolation. The flux data processed from the satellites come in two forms. One is an attempt to directly correlate CERES TOA fluxes to the fluxes on the surface of the Earth. The second is to determine radiative fluxes in the atmosphere. The specific details of CERES data collection can be found in Wielicki *et al.*, 1998.

### 2.2 S'COOL Data Collection

The Students' Cloud Observations On-Line program has less technical methods for collecting data; however, the data are invaluable to the CERES project. Students from over 500 schools around the world collect data at close to the same time the CERES instrument is passing overhead. These observations are used as the "ground truth" to compare to the cloud data derived for CERES. The ground truth data are used throughout the calibration process to help verify the cloud identification used by CERES. If there is a discrepancy in the two sets of data, the specifics of the data are analyzed to try to explain why there is not a perfect match. The reason for S'COOL is to help better understand all the data that are received from CERES and create a more solid, sound set of data for use in statistical studies.

## 3 Case Studies: Comparison of Datasets

### 3.1 Using FORTRAN to analyze large sets of data

In order to efficiently compare and contrast the ground and satellite data, FORTRAN programs were written. Because there are 639 entries for the satellite data, and over 4000 records of ground data, this was the most efficient manner for comparing the data. Initially, existing data files for 1997-1998 were analyzed and it was discovered that there were 45 time/space matches between satellite and ground datasets. New data were recently retrieved and processed automatically for the CERES instrument on TRMM for the months of April until August of 1998. During this time schools across the globe continued making ground observations. After these new data were repaired to account for a number for formatting problems, it was found that there were 99 matches total. This is more than twice as many matches as in the original comparison. These new match statistics were compared to the old match statistics to find any discrepancies in the data groups. In the tables below, the statistics of matching are displayed. The number of matches is listed, along with the y-intercept and slope derived using a least squared fit of the two datasets. If the two sets were graphed, they would have the listed slope and correlation as well. The “RMS sat-ground” value is the root mean square difference of the satellite and the ground values. The “Mean sat-ground” value is the bias between the satellite and the ground values. The comparison table is set up in a matrix form, in which the left-down diagonal is the line of total agreement. Any deviations from this line are places where the time/space data matches, but the observation differs. If the observation differs by only one level of agreement (such as the satellite observing clear while the ground observes a single layer of clouds) it is classified as a one class error. As the levels of disagreement move out, so do the classes of error. For the four by four matrix, it is possible to have up to three class errors, while in the three by three matrix, it is possible to have up to only two class errors. These errors are summarized beneath each table, and the total agreement is displayed as a percentage.

**New Dataset Matches**

Correlation of Cloud Amounts:
Number of Matches: 99 Correlation: 0.728 Slope: 0.775
Y-intercept: 13.9 Mean sat-ground: 4.6
RMS sat-ground: 30.3

**Comparisons of percentages of cloudiness seen by satellite vs. ground:**

| | | Ground | | | |
|---|---|---|---|---|---|
| | | Clear | Partly | Mostly | Overcast |
| S | Clear | 27 | 2 | 2 | 1 |
| A | Partly | 7 | 10 | 2 | 1 |
| T | Mostly | 5 | 3 | 12 | 7 |
| | Overcast | 0 | 1 | 8 | 11 |

60 out of 99 totally agree (60.6% agreement)

SUMMARY OF ERRORS

| Agree | 1-class | 2-class | 3-class |
|---|---|---|---|
| 60 | 29 | 9 | 1 |

**Comparisons of cloud levels seen by satellite and ground observers:**

| | | Ground | | |
|---|---|---|---|---|
| | | Clear | Single | Multi |
| S | Clear | 14 | 9 | 0 |
| A | Single | 3 | 29 | 3 |
| T | Multi | 3 | 29 | 9 |

52 out of 99 totally agree (52.5% agreement)

SUMMARY OF ERRORS

| Agree | 1-class | 2-class |
|---|---|---|
| 52 | 44 | 3 |

**Old Dataset Matches**

Correlation of Cloud Amounts:
Number of Matches: 45 Correlation: 0.779 Slope: 0.789
Y-intercept: 12.3 Mean sat-ground: 4.1
RMS sat-ground: 26.8

**Comparisons of percentages of cloudiness seen by satellite vs. ground:**

| | | Ground | | | |
|---|---|---|---|---|---|
| | | Clear | Partly | Mostly | Overcast |
| S | Clear | 13 | 1 | 0 | 0 |
| A | Partly | 4 | 6 | 0 | 1 |
| T | Mostly | 2 | 0 | 9 | 2 |
| | Overcast | 0 | 1 | 0 | 6 |

34 out of 45 totally agree (75.6% agreement)

SUMMARY OF ERRORS

| Agree | 1-class | 2-class | 3-class |
|---|---|---|---|
| 34 | 7 | 4 | 0 |

**Comparisons of cloud levels seen by satellite and ground observers:**

| | | Ground | | |
|---|---|---|---|---|
| | | Clear | Single | Multi |
| S | Clear | 6 | 4 | 0 |
| A | Single | 4 | 19 | 2 |
| T | Multi | 1 | 6 | 3 |

28 out of 45 totally agree (62.2% agreement)

SUMMARY OF ERRORS

| Agree | 1-class | 2-class |
|---|---|---|
| 28 | 16 | 1 |

3.2 Discrepancies in the datasets:

In theory, because the new data are simply the old data plus more data points, the new data comparison should have as many or more matches in each particular category as the old data. However, when the old dataset is compared to the new dataset, it can be seen that there is one place where this does not hold true. In the old data when the satellite shows a single layer of clouds and the ground shows clear, there are four matches. In the same place on the new dataset there are only three matches. To explain this problem, a program was written to ensure that all of the old data were in the new dataset. The program confirmed that this was true, but it also showed unexpected problems of formatting. The data were compiled over a number of years, and in this time, many different formats had been used. This caused a problem in the matching program because it is set to specific formatting requirements. After reformatting the data numerous times, it was concluded that the data in the old file, due to a formatting error, was placed in the category of single/clear in the old comparison, instead of clear/clear. This explains the single discrepancy in the old versus new comparison.

3.3 Statistical Analysis:

In order to understand the data, many different statistical analyses were performed. Initial comparisons dealt mainly with total agreement percentages, correlations, and time allowed for matching. From these comparisons it was seen that as time passes, the number of matches increases, while the remaining variables decrease. This was expected, because as the time allowed for matching increases, there should naturally be more matches. If one match falls within the 15-minute match period, it should also fall within any match period greater than 15 minutes. The other variables, such as correlation and slope, naturally decrease, because as time allowed for matching increases, there is more noise in the dataset. When the times of the observations do not match, there is always a chance that the clouds have changed in that amount of time. The farther apart in time the observations are, the more the clouds will have changed. The variables of slope, correlation, percent total agreement of cloudiness, percent total agreement of specific cloud levels, and percent total agreement of general cloud levels all decrease over time. Graphs of these data are in the appendices to this document.

This was a fair way to analyze the data for an overall idea whether the data were responding in the manner that was expected. However, for a more detailed understanding of whether or not the matching was random luck or more scientific, a new means of comparison was necessary. To do this analysis, the statistical method of chi squared was utilized. In this method, a table of any size is used to calculate a value for chi squared which is then turned into a percentage that determines how likely it is that the data is random or systematic. Using this method (detailed mathematical analysis is in the appendices to this document), it was found that is it highly unlikely that the agreement between the S'COOL schools and the CERES instrument is fortuitous. The chi squared values all indicated probabilities of chance of less than $1*10^{-4}$%. This value is amazingly low, and implies that there is almost no chance that the correlation between the datasets is by chance.

3.4 Validation Process:

The satellite to ground comparison is very important in validating CERES data. In a previous analysis (Rossow *et al.*, 1993) ground observations were also compared with satellite observations. The results from his experiment are similar to those obtained here, in that there is a large amount of matching where the two agree exactly and then it tapers off until there is a small amount of matching when the two disagree strongly. This is very similar to the data gathered through S'COOL and CERES, which provides a sense that the data were analyzed in a manner consistent with previous experimentation and with similar levels of agreement (Rossow *et al.* 1993).

3.5 Examining the Discrepancies:

In the new comparisons of ground to satellite data, there were some places where there were time/space matches, but the observations did not agree. When looking at the cloud levels comparison, there are 44 one class errors and 3 two class errors. (Examples of these types of errors can be found in the appendices.) In order to better understand why these errors were occurring, they were separated into categories. The problem areas occurred when the ground saw clear and the satellite saw a single layer (3 times), the ground saw clear and the satellite saw multiple layers (3 times), the ground saw a single layer and the satellite saw clear (9 times), the ground saw a single layer and the satellite saw multiple layers (29 times), and the ground saw multiple layers while the satellite saw a single layer (3 times).

There are many possibilities as to why the observations did not match. However, there are some central problems that were found in the comparisons. A problem in identifying clouds properly for the ground was simply the issue of converting local time to universal time. This was a problem because there are things such as daylight savings time that are often not taken into account during the conversion, giving an inaccurate time report, which causes the cloud report to also be incorrect. Another problem possibly encountered by the ground was that of the horizon. It is possible that landforms or buildings obstructed their field of view, and therefore they were not able to see all of the sky and give an accurate report of the entire sky. Related to this problem is the grid system used by the satellite to determine location. The satellite uses a pre-determined one-degree by one-degree grid, regardless of where the school might be. Therefore the satellite might have a very different view of the sky than the ground observers, and the cloud observations possibly would not match due to this problem. A final central issue is the problem of one thick cloud layer obscuring the view of another cloud layer, and therefore only one of the layers is reported. For example, if fog were to obstruct the view of the ground observers, they would not report high cirrus clouds, simply because they could not see them. These problems, among others, explain some discrepancies in the data comparisons.

### 3.5.1 Ground Clear and Satellite Single Layer (3 occurrences)

When the ground records clear and the satellite records a single layer, it is difficult to determine a set pattern because there are so few matches. Twice the satellite reports a low thick water cloud covering a small amount of the sky while the ground reports clear. This can possibly be explained due to the viewing conditions at the school site. It is possible that they have the problem of being in the corner of the satellite grid, or that landforms are blocking the view of the clouds. The final report is of high thin ice clouds covering a very small amount of the sky by the satellite and no clouds by the ground. These clouds could simply have been overlooked due to their small size, or any of the above listed reasons.

### 3.5.2 Ground Clear and Satellite Multiple Layers (3 occurrences)

Each time the ground reported clear and the satellite reported multiple layers, the satellite return showed a low thick water cloud and a middle thick water cloud. One of the three returns also had a high thick mixed cloud. It was reported that these clouds cover about half of the sky. It is possible that the time conversion was incorrect and therefore the observation incorrect. Also possible is the school being in the corner of the satellite grid or landforms obscuring the view of the clouds.

### 3.5.3 Ground Single Layer and Satellite Clear (9 occurrences)

In eight out of the nine reports of there being a single layer from the ground and no clouds from the satellite, the clouds reported by the ground were translucent or transparent cirrus-type clouds that covered 0%-5% of the sky. This seems to be a definite trend in the reporting system. There could be a problem with the satellite detection of high thin clouds. This problem is due to the fact that over land, where there is a variable surface underneath the clouds, it is difficult to discern the clouds. If the clouds are very thin and scattered, this becomes increasingly difficult. It was expected that the satellite would have difficulty viewing clouds such as these, and this data confirms that theory. The remaining report of satellite clear and ground single layer is the ground reporting an opaque stratocumulus cloud covering 50%-95% of the sky. It seems that this is likely a time mismatch. However, this observation was made in St. Louis, MO, which is very near the Mississippi River. Observations over variable landscapes are very difficult to make, and therefore it is possible that this record is simply a mistake in data recording.

### 3.5.4 Ground Single Layer and Satellite Multiple Layers (29 occurrences)

There are 29 matches where the ground reports a single layer when the satellite reports a number of layers. In all of these matches, there does not seem to be a trend of any sort, but there are possible explanations for these mismatches. One of these possibilities is the ground seeing an overcast layer of low cloud, such as fog or stratocumulus, making it impossible to see any cloud layers above the low level clouds. Another possible explanation is that of cloud edges. It is possible that the edges of the cloud are so partially filled that the satellite sees through them and measures both their temperature and the temperature of whatever is below them. Because temperature is key in the satellite determining of levels, they could possibly be placed in the incorrect level classification. The final explanation for this phenomenon is the arbitrary cutoffs for the satellite cloud levels. There are specific levels at which the satellite sees low clouds as opposed to middle or high clouds. If one single cloud spans more than one level according to the satellite, it will still be seen as a single cloud from the ground. When this occurs, the satellite would report multiple layers while the ground reports a single layer.

### 3.5.5 Ground Multiple Layers and Satellite Single Layer (3 occurrences)

Two times when the ground sees multiple layers and the satellite sees a single layer, the ground sees two layers of small amounts of clouds and the satellite sees one layer of a larger amount of cloud. The other instance of this occurrence, the ground sees half of the low sky covered with translucent stratocumulus, half of the middle sky covered with translucent altostratus, and half of the high sky covered with translucent cirrus. The satellite reports half the sky covered with a thicker altostratus cloud. It is possible that the students missed the time conversion, which was a common problem early in the experiment. It is also probable that the students are seeing multiple layers of clouds, as they report them, but the satellite sees only one thick layer and therefore does not detect the others as separate layers.

## 4 Conclusion

To better interpret the data collected by satellites, it is important to have some type of validation process. The S'COOL project makes it possible to better understand the data from the CERES instrument. By combining the ground and satellite datasets and using statistical analysis, it is possible to understand data gathered about clouds, find patterns in cloud detection, and find problems with both observation methods.

The knowledge gained through this comparison will enable problems such as these to be avoided in the future. For instance, knowing that the method used by the CERES instrument has problems in identifying high thin cirrus clouds will enable future researchers to create different detection algorithms that will more properly identify such clouds. Having the ground perspective to compare to the sky observations ensures that a more accurate picture of the sky will be provided. Using this "ground-truth" to understand problems with satellite-only observations will enable more precise cloud observations to be made with an unprecedented accuracy. With new algorithms more properly identifying clouds, it will be possible to create a more accurate global climate model.

In December of 2000, the Aqua satellite is scheduled to be launched with two CERES instruments on it. This satellite, along with Terra, will continue to provide data for comparison to S'COOL data. The S'COOL project continues to grow with new schools being added almost daily. S'COOL and CERES will yield even more information about clouds in the future, revealing much more about clouds and their effect on the global climate.

**Amanda Falcone**
Trinity University
Department of Engineering Science
715 Stadium Dr.
San Antonio, TX 78212-7200

## Acknowledgements

Dr. Lin Chambers
David Young
Barbara Maggi
The S'COOL Team
NASA Langley Research Center Employees and Researchers
Center for the Atmospheric Sciences Faculty, Staff, and Students
AURORA Interns

## References

CERES Brochure (1999) Available through National Aeronautics and Space Administration Langley Research Center. Document #NP-1999-04-069-GSFC.

CERES Homepage. [Online] Available *http://asd-www.larc.nasa.gov/ceres/ASDceres.html*, 7/20/00

EOS Homepage. [Online] Available *http://eos-am.gsfc.nasa.gov*, 7/20/00

ERBE Homepage. [Online] Available *http://www.larc.nasa.gov/org/pao/PAIS/ERBE.html*, 7/20/00

Rossow, W. B., A. W. Walker, L. C. Garder (1993). Comparison of ISCCP and Other Cloud Amounts. Journal of Climate **6**(12): 2394-2418.

S'COOL Homepage. [Online] Available *http://scool.larc.nasa.gov*, 7/20/00

Terra Homepage. [Online] Available *http://terra.nasa.gov*, 7/20/00

TRMM Homepage. [Online] Available *http://trmm.gsfc.nasa.gov*, 7/20/00

Wielicki, B. A., B. R. Barkstrom, B. A. Baum, T. P. Charlock, R. N. Green, D. P. Kratz, R. B. Lee, III, P. Minnis, G. L. Smith, T. Wong, D. F. Young, R. D. Cess, J. A. Coakley, Jr., D. A. H. Crommelynck, L. Donner, R. Kandel, M. D. King, A. J. Miller, V. Ramanathan, D. A. Randall, L. L. Stowe, R. M. Welch (1998). Clouds and the Earth's Radiant Enery System (CERES): Algorithm Overview. IEEE Transactions on Geoscience and Remote Sensing **36**(4): 1127-1141.

# Appendices

1 Matches Output for Comparison Program

2 Direct Data Comparisons

3 Explanation of Chi Squared

4 Chi Squared Calculations and Graphs for Cloud Percentages

5 Chi Squared Calculations and Graphs for Cloud Levels

6 Example of Comparison Between Two Satellite Instruments Using Chi Squared

7 Observation Mismatches in Ground and Satellite Data

8 Directories for Finding Programs and Files on iMac computer Quizno